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Weak interaction of photons and the process $\nu + Z \to \nu + Z + \lambda^+ + \lambda^-$

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Abstract. The cross section for the process $\nu + Z \to \nu + Z + \lambda^+ + \lambda^-$, where $\lambda^\pm$ represents $e^\pm$ or $\mu^\pm$, has been calculated from the point of view of the photon–neutrino weak coupling theory. The importance of this process to test the different theories of weak interactions has also been discussed.

1. Introduction

The weak interaction processes are generally considered in the framework of the current–current coupling theory. However, there are certain inherent drawbacks in this theory. For example, the theory is not renormalizable and it violates unitarity at high energies. As an alternative, vector boson theory has been suggested by different authors, but this theory also has these difficulties. Recently, Bandyopadhyay (1968) has proposed that photons can interact weakly with neutrinos and in view of this a certain class of weak interactions can be considered to be caused by this photon–neutrino weak coupling. The significant aspect of this coupling is that the high energy behaviour is consistent with unitarity and also the theory is renormalizable. The implications of this photon–neutrino weak coupling in various weak interaction processes and its possible role in astrophysics have been studied by Bandyopadhyay (1971) and Ray Chaudhuri (1970a, 1970b and 1971) in a series of papers. In this paper, we study the processes

$$\nu + Z \to Z + e^+ + e^- + \nu \tag{1}$$

$$\nu + Z \to Z + \mu^+ + \mu^- + \nu \tag{2}$$

from the point of view of photon–neutrino coupling theory. The processes are significant in the sense that the cross section can be enhanced by the increasing value of Z, the number of protons in a nucleus, and hence detection may become feasible. Thus, the processes can be utilized to test the validity of one or the other theory.

2. Cross section for the process $\nu + Z \to Z + e^+ + e^- + \nu$

From the Feynman diagrams (figure 1) for the process $\nu + Z \to Z + e^+ + e^- + \nu$, the scattering matrix element M_{fi} of this process is given by

$$M_{fi} = \frac{Ze^3 g}{(2\pi)^{7/2}} \left(\frac{m^2}{E_1 E_2 E_{\nu 1} E_{\nu 2}} \right)^{1/2} \frac{1}{|\boldsymbol{q}|^2}$$
$$\times \left\{ \bar{u}(p_2) \left(\gamma_\mu \frac{\mathrm{i}(\hat{k} - \hat{p}_2) - m}{(k - p_2)^2 + m^2} \hat{n} + \hat{n} \frac{\mathrm{i}(\hat{k} - \hat{p}_1) - m}{(k - p_1)^2 + m^2} \gamma_\mu \right) u(p_1) \right\}$$
$$\times \frac{1}{k^2} \bar{u}_\nu(q_2) \gamma_\mu (1 + \gamma_5) u_\nu(q_1). \tag{3}$$

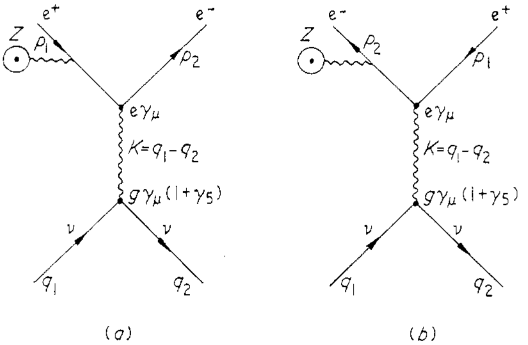

Figure 1. Feynman diagrams for the process $\nu+Z\to\nu+Z+e^++e^-$ according to the photon–neutrino weak coupling theory.

Here we have used the notation $\hat{p} = \gamma_\mu p_\mu$, g is the dimensionless photon–neutrino coupling constant which is taken to be $10^{-10}\, e$ (Bandyopadhyay 1968), q_1 is the four momentum of the initial neutrino and p_1, p_2, q_2 are the four momenta of the final positron, electron and neutrino respectively. q is the four momentum transfer to the nucleus and $\hat{n}$ is the polarization vector with $n^2 = -1$. Also k is given by the relation $k = q_1 - q_2$. The energy of the initial (final) neutrino is represented by $E_{\nu1}$ ($E_{\nu2}$) and E_1 and E_2 represent the energies of the positron and electron respectively.

Now

$$|M_{fi}|^2 = \frac{(Ze^3g)^2}{(2\pi)^7}\frac{1}{32E_1E_2E_{\nu1}E_{\nu2}}\frac{1}{|q|^4}\frac{1}{k^4}X \tag{4}$$

where X is given by

$$\begin{aligned} X = \mathrm{Tr}\Bigg\{\Bigg(&\frac{im\hat{n}\hat{Q}_2\gamma_\nu - m^2\hat{n}\gamma_\nu}{p_2k} + \frac{im\gamma_\nu\hat{Q}_1\hat{n} - m^2\gamma_\nu\hat{n}}{p_1k} \\ &+ \frac{\hat{n}\hat{Q}_2\gamma_\nu\hat{p}_2 + im\hat{n}\gamma_\nu\hat{p}_2}{p_2k} + \frac{\gamma_\nu\hat{Q}_1\hat{n}\hat{p}_2 + im\gamma_\nu\hat{n}\hat{p}_2}{p_1k}\Bigg) \\ &\times\Bigg(\frac{m^2\gamma_\mu\hat{n} - im\gamma_\mu\hat{Q}_2\hat{n}}{p_2k} + \frac{m^2\hat{n}\gamma_\mu - im\hat{n}\hat{Q}_1\gamma_\mu}{p_1k} \\ &+ \frac{\gamma_\mu\hat{Q}_2\hat{n}\hat{p}_1 + im\gamma_\mu\hat{n}\hat{p}_1}{p_2k} + \frac{\hat{n}\hat{Q}_1\gamma_\mu\hat{p}_1 + im\hat{n}\gamma_\mu\hat{p}_1}{p_1k}\Bigg)\Bigg\} \\ &\times \mathrm{Tr}(\gamma_\nu\hat{q}_1\gamma_\mu\hat{q}_2 - \gamma_\nu\hat{q}_1\gamma_\mu\hat{q}_2\gamma_5) \end{aligned} \tag{5}$$

where

$$\begin{aligned} Q_1 &= k - p_1 = q_1 - q_2 - p_1 \\ Q_2 &= k - p_2 = q_1 - q_2 - p_2. \end{aligned} \tag{6}$$

The calculations of traces of the expression for X in the coordinate system for which

$$\mathbf{p}_1 + \mathbf{p}_2 = 0 \tag{7}$$

have been carried out and in the relativistic case for which E_1 ($=E_2$), is considered to be very large compared with the mass m of the electron (positron). Neglecting the momentum transfer to the nucleus, we have for X

$$X = \frac{256 E_{\nu 1} E_{\nu 2}}{(E_{\nu 1} - E_{\nu 2})^2 - E^2 \cos^2\phi} \{-(E_{\nu 1} - E_{\nu 2})^2 \cos\theta \cos\psi + E(E_{\nu 1} - E_{\nu 2})(\cos\theta + \cos\psi)\cos\phi - E^2 \cos^2\phi\} \tag{8}$$

where

$$\theta = \widehat{\mathbf{p}_1 \cdot \mathbf{q}_1}$$
$$\phi = \widehat{\mathbf{p}_1 \cdot \mathbf{q}} \tag{9}$$
$$\psi = \widehat{\mathbf{p}_1 \cdot \mathbf{q}_2}$$

and E is the energy transfer to the nucleus. Thus

$$|M_{fi}|^2 = \frac{8(Ze^3 g)^2}{(2\pi)^7} \frac{1}{E_1{}^2 E^4} \frac{1}{\{E^2 - (E_{\nu 1} - E_{\nu 2})^2\}^2 \{(E_{\nu 1} - E_{\nu 2})^2 - E^2 \cos^2\phi\}} \times \{-(E_{\nu 1} - E_{\nu 2})^2 \cos\theta \cos\psi + E \cos\phi(\cos\theta + \cos\psi)(E_{\nu 1} - E_{\nu 2}) - E^2 \cos^2\phi\}. \tag{10}$$

From this, we can compute the differential cross section

$$\frac{d\sigma}{d\Omega_{p_1}\, d\Omega_{p_2}\, d\Omega_{q_2}\, dE_1\, dE_2\, dE_{\nu 2}} = \sigma_0 \frac{E_1{}^2 E_2{}^2 \delta(2E_1 + E + E_{\nu 2} - E_{\nu 1})}{E^4 \{E^2 - (E_{\nu 1} - E_{\nu 2})^2\}^2 \{(E_{\nu 1} - E_{\nu 2})^2 - E^2 \cos^2\phi\}} \times \{-(E_{\nu 1} - E_{\nu 2})^2 \cos\theta \cos\psi + E(E_{\nu 1} - E_{\nu 2}) \cos\phi(\cos\theta + \cos\psi) - E^2 \cos^2\phi\} \tag{11}$$

where

$$\sigma_0 = \frac{32\pi^2 (Ze^3 g)^2}{5(2\pi)^7}. \tag{12}$$

In the crude approximation, considering E and $E_{\nu 2}$ to be very small compared to $E_{\nu 1}$ and taking $E_{\nu 1} = E_1$, we can write

$$\sigma \simeq 0{\cdot}33 \times 10^{-50} \frac{Z^2}{E_{\nu 1}{}^2} \tag{13}$$

where $E_{\nu 1}$ is in MeV.

For $Z = 10, 26, 32$, the cross sections are respectively

$$\sigma \simeq \frac{0{\cdot}33 \times 10^{-48}}{E_{\nu 1}{}^2}$$
$$\sigma \simeq \frac{2{\cdot}25 \times 10^{-48}}{E_{\nu 1}{}^2} \tag{14}$$
$$\sigma \simeq \frac{2{\cdot}24 \times 10^{-47}}{E_{\nu 1}{}^2}.$$

The cross section of the process (2) is similar to that of process (1) in the relativistic case as considered here.

3. Discussion

According to the current–current coupling theory of weak interactions, the processes $\nu_e+Z \to \nu_e+Z+e^-+e^+$ and $\nu_\mu+Z \to \nu_\mu+Z+\mu^-+\mu^+$ are allowed on the basis of the selfcurrent interactions $(\nu_e e)(\nu_e e)$ and $(\nu_\mu \mu)(\nu_\mu \mu)$. However, the processes $\nu_e+Z \to \nu_e+Z+\mu^-+\mu^+$ and $\nu_\mu+Z \to \nu_\mu+Z+e^-+e^+$ cannot occur according to the current–current coupling theory unless it is considered that the neutral lepton currents such as $(\bar{\mu}\gamma_\mu(1+\gamma_5)\mu)$, $(\bar{e}\gamma_\mu(1+\gamma_5)e)$, $(\bar{\nu}_\mu\gamma_\mu(1+\gamma_5)\nu_\mu)$ and $(\bar{\nu}_e\gamma_\mu(1+\gamma_5)\nu_e)$ exist. However, the existence of these neutral lepton currents having the strength of the universal Fermi coupling is in contradiction to the experimental results. Indeed, Albright and Oakes (1970) have found an upper limit for

$$\frac{\sigma(\nu_\mu + p \to \nu_\mu + p)}{\sigma(\nu_\mu + n \to \mu^- + p)} \leqslant 0{\cdot}12 \pm 0{\cdot}06. \tag{1}$$

Thus these processes can occur according to the current–current coupling theory either with a reduced coupling strength or when an electromagnetic form factor for neutrinos is introduced. It is noted that according to the vector boson theory the above two processes are not allowed unless a neutral vector boson exists. However, according to the photon–neutrino weak coupling theory, the processes $\nu_e+Z \to \nu_e+Z+\mu^-+\mu^+$, and $\nu_\mu+Z \to \nu_\mu+Z+e^-+e^+$ are allowed. So, the detection of these processes will provide a crucial test for the validity of the photon–neutrino weak coupling theory.

It should be observed that to test the nature of the electron–neutrino interaction, we must depend on laboratory experiments. Recently, Reines and Gurr (1970) have reported an upper limit for the cross section of the process $\bar{\nu}_e+e^- \to \bar{\nu}_e+e^-$ which is found to be four times larger than that predicted with the V−A theory. Chen (1970) has derived the upper limits for interactions other than V−A such as V+A, S, P, T, V and A and has found that the corresponding upper limits are lower than that for the V−A interaction. In particular, leptonic neutral current interactions of the vector or axial-vector type are already constrained to be below the strength of a Fermi interaction. Banyopadhyay and Ray Chaudhuri (1971) have shown that the present experimental upper limit for the cross section as reported by Reines and Gurr is about 200 times the cross section predicted with the photon–neutrino weak coupling theory. With improvements recently made on the experimental apparatus, it appears possible that the present upper limit for reaction (1) will be lowered in the near future and this will allow us to draw important conclusions about the nature of the electron–neutrino interaction.

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